Basic concepts on rheology and application of shear-thickening fluids in protective gear

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Abstract

The current manuscript aims to describe and introduce the nature of the fluids that are usually observed in the environment and brings the suggestion on how dilatant fluids can be applied for protective gear. It explains how these fluids influence in the equipment and why it is a good idea to use them for such situations. In the study of fluid mechanics, the fluid is the main important component to be taken into account, however, it can be classified as Newtonian and non-Newtonian fluid. It is important to understand the behaviour of such fluids so that one can predict the alterations and their responses under various conditions. Newtonian and non-Newtonian fluids have very different characteristics and the following study focuses on underlying the similarities and discrepancies. The discipline called Rheology is the one that focuses on these types of fluids and the deformation that they go through when stresses are applied. The term can be divided in “rheo”, which has origins from Greek and means flow and “logia”, which means study of. Therefore, Rheology means study of flow. It has focused majorly in the study of fluids, however, lately, there has also been some focus on the study of deformation of solids and some other substances that are called viscoelastic materials [8, 9, 13]. By understanding the rheology of the dilatant fluids, it was possible to understand the benefits that the use of this fluids can offer when there is a need in the society, such as to improve the efficiency and efficacy of the body armours. In engineering, it is important to find solutions to issues that are observed in the society and facilitate the processes, advising for improvements that make humans’ lives easier. The main issue in cause here is that the already existent body armours are, first too heavy, because there has been need to compensate with weight, to improve the protection and they are not effective in protecting the person who wears them from the impact, many times bruises being cause in the process and people remaining with some type of pain after the impact. This study is important for suggesting an alternative, which are the liquid body armours, with use of shear-thickening fluids in their constitution. The explanations regarding the impact of stresses on such materials and the suggested applications are presented in the next pages of this paper.

Keywords Rheology · Dilatant fluids · Non-Newtonian fluids · Body armours

1 Introduction

Before going deeper into the topic, it is important to clearly define the term Rheology. Rheology is the science of deformation of materials. [Wilson [14]] The term derives from two words of Greek origin: “rheo”, meaning flow and “logia”, that signifies study of. Rheology can then be defined as the study of flow. This flow can be of fluids

(liquids, gases, viscoelastic materials, etc.) or, related to the deformation of solids under the application of some type of stresses [8].

Rheology is a science that focuses on understanding how the materials (being them liquids, gases, etc.) react to force being applied to them. This impact is accounted as stress, which is the ratio between the force being applied and the unit area. The force may cause a response in terms of

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quantity of deformation or even in terms of what is called strain rate [13, 14].

In general, materials that are considered to be elastic react instantaneously to a deformation; however, when the material is viscous, the reaction is proportionally related to the rate at which this deformation is happening.

When it comes to this science, there are several expressions that need to be known and well understood so that previsions about their behaviour can be made. The fluids that are studied can be separated into two major groups. They are Newtonian fluids and the non-Newtonian fluids. Furthermore, these terms are explained in detail, to help understanding why the characteristics of these fluids are so important for the problems in cause.

2 Useful concepts

A few concepts need to be explained further in order to understand the nature of these fluids. These concepts are:

1. **Viscosity:** it is simply the resistance that the fluid offers to any stress applied, that may cause a change in the profile or in its movement relatively to other portions of the fluid or things in the vicinity; viscosity is the reciprocal of fluidity and represents the opposition to flow. It is represented with the symbol μ and can be defined as the ratio between the shearing stress and the rate of change of velocity over time. The viscosity is usually presented in terms of dynamic viscosity (absolute viscosity) or even kinematic viscosity. The dynamic viscosity measures the necessary force to overcome the friction in the interior structure of the fluid; dynamic viscosity is defined as the tangential force per unit area needed to move the fluid in one horizontal plane with respect to other plane with a unit velocity while the fluid's molecules maintain a unit distance apart [5]. On the other hand, the kinematic viscosity quantifies the ratio of the dynamic viscosity to the density of the fluid to be studied [12].
2. **Shear:** can be defined as the strain that is created when the layers of the fluid are shifted in comparison to others, because of the application of some pressure over the structure of the fluid. One concept that needs to be looked into detail is shear rate; this is the proportion at which the different layers of the fluid will move past the neighbouring layers; it is dependent on the geometry of the flow and also on its speed.

3 Newtonian fluids

Some fluids present a stress that is linearly relational to the strain at each point of it. The stress and the strain are directly proportional. These are called Newtonian Fluids. There are several examples of Newtonian fluids that are used in everyday life, such as water, hydrocarbons (oil and gas), alcohol, glycerine and many others.

Basically, as there are variations on the shear rate, the viscosity of these fluids remains constant. Most organic fluids and also dilute aqueous solutions are considered to have this type of behaviour. In these fluids, the viscosity remains constant, unless the temperature or the pressure is changed; they don't change viscosity when forces are applied to them.

The suspension of simple particles on Newtonian fluids can cause these to behave as non-Newtonian fluids as a consequence of the interactions that happen between the particles within the fluids [10, 11].

4 Non-Newtonian fluids

There is a second category of fluids, which do not have the same characteristics as the Newtonian fluids. These are shear sensitive and oppose shearing action. They don't have a linear relationship; therefore, the viscosity varies as the shear stress being applied or the shear rate changes.[7, 10] There are several types of fluids with non-Newtonian behaviour. They are viscoplastic fluids, Bingham fluids, rheopectic, dilatant, pseudoplastic, thixotropic, etc.

Although the majority of naturally found non-Newtonian fluids are classified as pseudoplastics, there is also a large quantity of dilatant fluids in nature, such as the quicksand. This non-Newtonian behaviour surges when the components in a fluid interact.

5 Dilatant materials (shear thickening fluids)

These are the main concern of this study, as they have the properties we are looking for when it comes to enhance the characteristics of the body armours. Following are some basic concepts about the dilatant fluids.

Dilatant materials are also known as shear thickening materials. Their behaviour is characterized by the increase of the viscosity when the applied rate of shear strain is increased; when they are pushed harder, they tend to feel more resistant against the force being applied.

This type of materials can be found in laboratories or be created by scientists but can also exist in household environments and can be created at home. One good example is the dilatant fluid that can be created from corn flour. Another very known example of dilatant material is the wet sand found in beaches or other muddy locations. It can be observed that depending on the way the force is applied, one could sink in the sand or not. In case of encountering wet sand, one could sink in if the person stood still (the fluid has then low viscosity and behaves as a lubricant) but the effect would be different if running across the sand (the shear stress is capable of overcoming the repulsive forces that exist in between the particles and there are forces that combine the particle motions, forming hydroclusters) [9]. It is as if a liquid behaved as a solid depending on the circumstances [6]. Another good example of dilatant fluid is the mixture of corn-starch and water, which also has this particular type of behaviour.

Several factors control the behaviour of the dilatant fluids, namely, the profile, particle size, spreading and the proportion of particle density that are suspended in the fluid. The so-called suspension observes this behaviour when it changes from a stable state to one of flocculation, under the application of some type of stress [3]. This happens because in cases where the material is subjected to high levels of stress, they quickly become very stiff.

There have been studies on the applications of shear thickening fluids; it has been noticed that this type of material can be used for many commercial applications such as body armours, sporting protective clothing and other products.

In shear thickening materials, there is formation of hydroclusters, as mentioned previously. There is slight repulsion between the particles, which allows them to float in the surface of the fluid without them tramping together or settling at the down part of the fluid. When there is an abrupt impact on the surface of it, the energy overpowers the forces in the particles, and they don't initially separate from one another; the repulsive forces are overcome by the energy of the impact. As soon as this energy disappears, the repulsive forces return back to their action and the hydroclusters are "destroyed" and the now apparently solid and stiff material behaves again as a fluid.

This principle has been applied commercially these days, for equipment such as body armours [3]. In the past, these armours would be effective to protect the body against threats and shocks but limited the wearer's ability to move and execute the task required, because of the stiffness and bulkiness of the equipment. The use of fluids with dilatant properties has improved the mobility and flexibility, and also contributes for the protection. These properties allow the distribution of the impact along the armour. However, studies have still been conducted to

improve the efficacy of armours created making use of these properties, so that they offer a strong protection and possess high penetrability to air and humidity and it becomes comfortable to be worn.

6 Use of shear-thickening fluids for protective gear

Recently, there have been a huge amount of studies that aim to look into the applications of shear-thickening fluids to solve problems that have been observed in protective gear. This paper is going to introduce this new technology and explain how it helps and contributes for this industry.

Dilatant fluids can be used in the fabrication of protective gear or equipment. They are used for body armours, vests, army gear and other types of materials used for protection. This has been done because researchers have realised the commercial potential of dilatant fluids. The industries can make use of the rheological properties, the methods to fabricate such fluids, the mechanisms involved in the shear thickening processes and other factors.

Dilatant fluids were not always seen as good substances, however, once their potential has been discovered, the industries have been trying to make the best use out of it. The mechanisms used for the protective gear is the one already explained previously. The shear thickening results from a stable suspension becoming flocculated due to forces experienced under shear [4].

One of the things that greatly influences the shear thickening behaviour is the fraction of particles present in the substance; a greater particle fraction will increase the probability of interactions and influences between one another. Because of the high fractions, the suspension of the particles and the effect on the flows of the particles tend to increase [4].

The recent studies about the shear thickening mechanisms have been focusing more on the qualitative accounts of the phenomenon; early studies have mostly been quantitative. Currently, the researchers look into the microstructure of the substances. The current studies on hydroclusters have currently been a gain to the industry of protective gear. They usually make the combination of the shear thickening fluid with fabrics, to make use of the properties of the fluid. The main focus is that as these materials receive an impact, they are able to protect the wearer and still perform the task that they are designed for; usually the objective is to dissipate the energy of the impact.

The dilatant fluids can be applied in protective clothing such as body armours. Not many armours have been to this day, able to offer protection and at the same time, give good flexibility and mobility to the person who wears

them. This is because the materials used to design them might have a greater stiffness in order to sustain the possible impacts that the equipment will have to endure. Researches have been made in places such as the University of Delaware and the US Army Research Laboratory, where it is made use of dilatant materials to be applied in military equipment, ballistic and other important aspects [4]. Tests have been made with the fluids and they have been proved to be effective in both offering protection and allowing the wearers to perform the tasks. For this reason, several patents are continuously being filed for armours made of this type of technology. They might all be similar, because the principle behind them is basically the same. There is basically a similar process in the majority of these processes. They usually dilute the dilatant fluid in ethanol, saturate Kevlar with the fluid that has been diluted and subsequently, the mixture is put in the oven to evaporate the remaining free ethanol [4]. The effect is that when the impact on the gear is received, the dilatant fluid causes it to harden and it makes the armour more efficient and capable of sustaining the force. As soon as the impact has been released, the armour turns back to its initial state and becomes flexible again [2]. This is a transition that happens very fast, in a question of milliseconds. Comparisons of armours made using this material with those that do not possess this technology have been made and observations have been that the combination of shear thickening fluids with the usual fabric have presented higher resistance to the impact.

According to Ding et al. [4], the majority of the liquid body armours have been designed by immersing the fibrous substrate or an absorbent media in the dilatant fluid; however, what has been observed is that there is a disadvantage that when the fluid is exposed to those elements, the performance of the fabric decreases since the fluid is vanishing and leaking. There have been tentatives to solve this issue and one of them was to use hollow fibres. But another issue has appeared. Based on Borella et al. [1], as referred to by Ding et al. [4], the dilatant fluid cannot be easily pumped into this type of fibres. For this to happen, there is a need to decrease the viscosity of the fluid, but even this method would negatively impact the properties of the fluid itself and because of that, the gains that are aimed to be obtained from the process are lost.

Many other studies continue to be conducted in the United States of America to see how the shear thickening fluids can be used for the military equipment and how to overcome the drawbacks that have been observed so far. Plus, researches have been done in the recent years to find out if engineered materials could be used to improve the performance of the gear. One of the examples of materials that have recently been studied in the UK is called de-three-oh (d3o), however, not enough research has been

done so far, in order to draw conclusions. What is already known is that it is capable of absorbing the energy of the impact.

7 Practical application

As mentioned before, the shear-thickening fluids are suggested for the use in protective gear. This is a study on how those properties of the fluids apply and improve the equipment. For starters, it is important to take into account that shear-thickening fluids are composed of liquids and particles that are called colloidal. The materials that have been already been used cannot provide appropriate protection to the whole body because they cause stiffness and they have bulky properties. Therefore, by associating the properties of shear-thickening fluids can be a way to overcome these drawbacks.

The major application of the shear-thickening fluids is seen in the following manner: in the body armours, there is use of these fluids for the production of body armours. The most advisable technique would be to use Kevlar in the confection. Kevlar is basically a type of plastic, which is very strong. It is not a type of material that can be created by any scientist or in the lab but is produced by a company called DuPont™. The Kevlar is supposed to be drenched in the shear-thickening fluid. As explained before, tiny particles of the fluid are suspended, and they tend to cause repulsion to one another. This causes the particles to float and not being compacted into one solid structure, however, when there is a sudden impact, the particles no longer will repel each other, and they will stay together. This structure which is suddenly created is called hydro-clusters and it is what confers the protective properties of the armours [3, 7, 15].

In the creation of the armour, through research, it was discovered that it is necessary to first mix the fluid in some type of alcohol, preference given to ethanol. The mixing of the solid and liquid particles can be done using devices which can be ultrasonic, mechanical or magnetic. The reason why the alcohol is necessary is because impregnating fabrics is not very easy, without dilution, given that shear-thickening fluids are viscous materials; the alcohol has no real effect on the process, apart from facilitating the dilution. Afterwards, the plastic (Kevlar in this case) must be saturated with the fluid, which has been diluted previously and this saturated mixture must then be put into the oven in order to dissolve the alcohol that was initially added. This is where the shear-thickening fluid acts to make the Kevlar more permeable and the Kevlar helps also to keep the fluid how it should be and not moving. Thanks to this technique, the structure becomes flexible and acts in according to the force being applied. If an object hits the

armour, because of the presence of the fluid, it is instantly hardened, and the Kevlar becomes stronger.

The use of shear-thickening fluids can, not only be used with Kevlar, but also with other fabrics, such as Technora, Twaron or Dyneema, to improve the flexibility when there is no impact and resistance once the impact happens.

This procedure just helps to prove that shear-thickening fluids indeed improve the penetration forces and also improve the resistance of the equipment. I would suggest the application of this process for protective armours for the police or other entities responsible for the protection of the country, because it reduces the necessity of creating heavier armours, which were in the past considered to be more effective in responding to impacts.

8 Conclusion

The paper introduces the basic concept of Rheology and suggests the use of shear-thickening fluids in body armours and body-protection equipment. It shows how the process of adding these substances works and how the fluids help in enhancing the equipment.

It is clear that Rheology it is a very broad science and that many concepts make part of it. There are basically two types of fluids, which are, Newtonian and non-Newtonian fluids. There are several examples of Newtonian fluids in our daily lives, such as water, hydrocarbons and others [8].

Among the non-Newtonian fluids, there are dilatant, shear-thinning, thixotropic, viscoplastic and rheopectic fluids. They are all characterised by the variation of the viscosity as a function of the shear rate on the fluid. The shear thickening fluids have been receiving plenty attention lately, especially in the industry of protective gear. These fluids have proven to decrease the stiffness of the equipment and the variation of the viscosity helps to improve the flexibility of the equipment. However, due to the drawbacks that have been observed, it is necessary to conduct more studies on how to improve the mechanism and make it more efficient and improve the efficacy.

The industry should invest in these researches and encourage new studies because it is clear that the dilatant fluids offer many advantages that cannot be overlooked. Another very important aspect of it is that this is a very cost-saving technique, given that in order to create the shear thickening properties, the necessary materials or ingredients are not very expensive.

There is now a world of possibilities because of this new technology that has been studied. However, although the dilatant fluids have been the main focus globally, it would be a good step to look now into the benefits of the other types of non-Newtonian fluids, because they might also be very useful for other

industries and areas that are highly dependent on the viscosity of the materials. It is time now to take these fluids out of the laboratories and implement their properties into daily life issues, so that they can be used to solve the problems of the populations. Surely, with the advance of researches and technologies, the world is looking forward to a new era, where the focus is not only on those fluids whose behaviour is already known and understood (Newtonian fluids), but also into what for so long had been a mystery.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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